Magnetic monopole searches in the cosmic radiation

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Abstract

There has been a big effort in the past twenty years with at least a couple of generations of experiments which searched for supermassive GUT magnetic monopoles in the cosmic radiation. Here a short review of these searches is given, together with a brief description of the theoretical framework and of the detection techniques.

1 Introduction and theoretical framework

While the existence of magnetic monopoles is not excluded by classical electromagnetism, the first convincing argument in favor of such particles was made by Dirac in 1931, showing that the existence of one single monopole could explain the observed quantization of the electric charge [1]. A big jump in the magnetic monopole research was made in the seventies when 't Hooft and Polyakov [1] showed that each time a semi-simple non abelian gauge group (*e.g.* SU(N)) is broken leaving a residual $U_{em}(1)$ subgroup, magnetic monopoles are produced as topologically stable soliton solutions of the theory. Their mass m is of the order of the energy scale at which the symmetry breaking takes place. A cosmological production of magnetically charged point-like topological defects (via the Kibble mechanism) is then foreseen in the framework of Grand Unified Theories (GUT). This results in a flux of super-massive monopoles with $m \sim 10^{17}\,$GeV. Lower masses ($m \sim 10^{10} \div 10^{15}\,$GeV) can results from GUT theories with intermediate scale symmetry breaking [1]. At our time monopoles can be searched for in the penetrating cosmic radiation as “fossil” remnants of these early transition(s).

Unfortunately no definite prediction can be made on the monopole flux. It would be either too large in classical cosmology (the so called *monopole problem*), or too low, practically undetectable, in an inflationary scenario, or at a measurable level if thermal production is assumed after the inflationary phase. However, some upper limits can be obtained from arguments based on magnetic field survival or mass density. By requiring that monopoles do not short-circuit the galactic magnetic field faster than the dynamo mechanism can regenerate it, an upper limit on their flux can be obtained. This is the so-called Parker bound ($\sim 10^{-15}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ [1]), whose value sets the scale of the detector exposure for monopole searches. Under some assumptions, an Extended Parker Bound (EPB) at the level of $1.2 \times 10^{-16}(m/10^{17}\,\mathrm{GeV})\ \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ was also obtained [1]. Another upper limit can be obtained by requiring that the monopole flux is such that the related mass density do not overclose the Universe (the *closure bound*). If, as suggested by Rubakov and Callan [1], GUT magnetic monopoles catalyze nucleon decays along their path with a cross section σ_c of the order of the hadronic cross sections, a different set of flux limits can be obtained based on the observed luminosity of astrophysical objects (*e.g.* neutron stars) in which monopoles could be gravitationally captured. These limits are very stringent (few orders of magnitude below the Parker bound) but they rely on strong assumptions on the physical properties (e.g. magnetic field strength and configuration) of the interested region [1].

The velocity range in which GUT magnetic monopoles should be sought spreads over several decades. If sufficiently heavy ($m \gtrsim 10^{16}\,\mathrm{GeV}$), they would be gravitationally bound to the galaxy with a velocity distribution peaked at $\beta = v/c \simeq 10^{-3}$. Lighter monopoles, with masses around $10^{7} \div 10^{15}\,\mathrm{GeV}$, would be accelerated to relativistic velocities in one or more coherent domains of the galactic magnetic field, or in the intergalactic field, or in several astrophysical sites like a neutron star [1].

2 Detection techniques and experimental searches

Experiments aiming to perform a sensitive GUT monopole search below the Parker bound need very large acceptances (*i.e.* thousands of $\mathrm{m}^2\mathrm{sr}$), good sensitivity in a wide velocity range going from $\beta \simeq 10^{-5}$ up to $\beta \simeq 1$, and livetimes of the order of at least few years. These needs forced the optimization of the detection methods which can be classified into *Induction*, *Energy Loss* and *Catalysis* based *Techniques*

Experiment	Detection Technique	Location
Kolar Gold Field	gas detectors	KGF mine (India)
Baksan	scint. counters	Baksan valley (Russia)
Soudan	gas detectors	Minnesota (USA)
Ohya	CR-39 track-etch	Ohya quarry (Japan)
MACRO	scint. + gas + track-etch	Gran Sasso (Italy)
AMANDA	Čerenkov light	South Pole
Baikal	Čerenkov light	Baikal lake (Russia)

Table 1: List of the main experiments that are (or have been) performing direct searches with *Energy Loss Techniques* [1].

(hereafter IT, ELT and CT respectively). These have been used for both direct and indirect searches for monopoles. Here we will briefly go through their main results.

A magnetic charge passing through a loop of wire induces a current jump that can be subsequently detected. This detection principle is by far the the best one for the search for magnetic monopoles since it does not depend on other characteristics like velocity, mass, electric charge, and it works also if the monopole comes with an attached proton or heavier nucleus (these bound systems might form due to the magnetic charge-moment interaction). Nevertheless the difficulty and cost of building large arrays limited this technique to sensitivities to fluxes orders of magnitude above the Parker bound. The combination of the IT results gives an upper limit [1] of $\sim 2 \cdot 10^{-13}$ cm^{-2}s^{-1}sr^{-1} [1].

The energy loss of GUT magnetic monopoles across different kind of materials strongly depends on their velocity [1]. Therefore different detectors and analysis strategies have to be adopted to search for monopoles in different β ranges. The peculiar property of a fast magnetic monopole with $\beta \gtrsim 10^{-2}$ is its large ionization power compared either to the considerably slower monopoles or to minimum ionizing electrically charged particles. On the other hand, slow magnetic monopoles should leave small signals spread over a large time window. It is therefore difficult to have good sensitivity in a wide velocity range within a single experiment. Many experiments have been done (or are currently running) in order to perform direct or indirect searches for monopoles by using ELT's in various β regions.

Direct searches have been performed by a number of experiments, each of them exploiting a different aspect of the ELT. Some of them are listed in tab.1, together with the detection technique used in the search. Here we will very briefly describe two of them, namely MACRO

[1] All the upper limits will be given at 90% C.L.

Experiment	Technique	Flux limit	β range
Soudan1	gas detectors	$8.8 \cdot 10^{-14}$	$10^{-2} \div 1$
IMB	Čerenkov light	$1 \div 3 \cdot 10^{-15}$	$10^{-5} \div 10^{-1}$
Kamiokande	Čerenkov light	$2.5 \cdot 10^{-15}$	$5 \cdot 10^{-5} \div 10^{-3}$
Baikal	Čerenkov light	$6 \cdot 10^{-17}$	$\sim 10^{-5}$
MACRO	Streamer tubes	$3 \cdot 10^{-16}$	$1.1 \cdot 10^{-4} \div 5 \cdot 10^{-3}$

Table 2: Flux upper limits limits (in $cm^{-2}s^{-1}sr^{-1}$) obtained by experiments searching for nucleon decays catalyzed by a GUT monopole (reprinted from [5]).

and AMANDA.

MACRO was a large multipurpose underground detector mainly optimized for the search for GUT magnetic monopoles with velocity $\beta \geq 4 \times 10^{-5}$ and with a sensitivity well below the Parker bound. The apparatus, which took data up to December 2000, was arranged in a modular structure and had a total acceptance of $\sim 10,000\,\mathrm{m}^2\mathrm{sr}$. Redundancy and complementarity in monopole searches were provided by the use of three independent detection techniques: scintillation counters, limited streamer tubes and track-etch detectors. Dedicated hardware and analysis procedures were adopted to search for monopoles in different β ranges with different subdetectors. This allowed, for the first time, a sensitivity well below the Parker bound in a very wide velocity range. As shown in fig.1, a limit of $\sim 1.5 \cdot 10^{-16}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ was put for monopoles with $\beta \gtrsim 10^{-4}$ (see [2] for further details).

AMANDA is an array of strings of photomultipliers, located deep under the ice of South Pole, mainly devoted to the search for very high energy neutrinos. It is sensitive to monopoles through the detection of the huge amount of Čerenkov light emitted by relativistic ($\beta \gtrsim 0.8$) magnetic charges [3]. Due to the high transparency of the ice and to the dimensions of the array, the acceptance is very large, then a good sensitivity to very low fluxes is ensured. However, due to the detection principle itself, such sensitivity is confined in a very narrow region around $\beta \sim 1$ [3]. This is nonetheless interesting because of the possible connection between relativistic light GUT monopoles and cosmic ray events above the GZK cutoff (see sec.3).

Indirect searches can be performed by looking for monopole induced tracks in ancient mica crystals. If a monopole-nucleus bound system crosses a piece of such materials a permanent damage is produced along the trajectory, that can be subsequently evidenced through a chemical etching. Since these crystals have been exposed for very long times ($\sim 10^8\,\mathrm{yr}$), very strong upper limits, at the level of 10^{-18} $\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$, can be obtained [4]. However, since the detection threshold is large, this technique is sensitive in a limited β region around $\beta \sim 10^{-3}$ and the formation of a stable monopole-nucleus bound system must be assumed. In other kinds of indirect searches, the experiments look for monopoles trapped in bulk matter (*e.g.* iron sand) [1].

If GUT monopoles catalyze nucleon decays along their path with a sufficiently large cross section, direct searches can be performed also by means of the detection of the decay products (CT). As a consequence many of the detectors originally built for nucleon decay searches have been used to look for monopoles. Detectors like AMANDA or Baikal, are also sensitive to monopoles by detecting the Čerenkov light emitted by the decay products. MACRO performed a sensitive search for catalysing magnetic monopoles with its streamer tube system [5]. The results of these searches are summarized in tab.2.

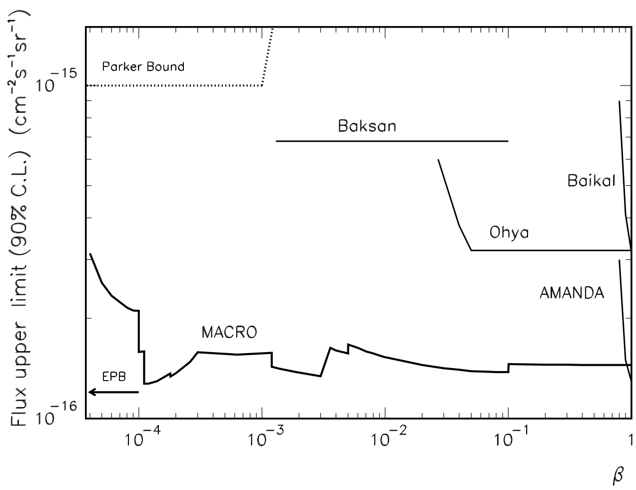

Figure 1: The global 90% C.L. upper limits to an isotropic flux of bare magnetic monopoles obtained by several experiments in direct searches, without the assumption of monopole induced nucleon decay catalysis (reprinted from [2]).

3 Discussions and conclusions

The null result obtained by several experiments in a wide velocity range put very stringent limits to the local monopole flux that will be hardly improved by other searches and that represent a strong weir against future theoretical speculations. Some of the more stringent results, referring to direct searches for bare monopoles, are shown in fig.1. As can be seen the MACRO result covers the whole region ensuring the highest sensitivity and putting a strong upper limit, while underwater/ice experiments seem very promising in the ultrarelativistic regime only (unless nucleon decay catalysis is assumed). Strong upper limits have also been put with indirect searches or under the hypothesis of a monopole induced catalysis of nucleon decays.

Since theory is unable to give a reasonable prediction on the expected flux, with a negative result one cannot put stringent conclusions on GUT and/or cosmology, except for some superstring models that foresee fluxes at the level of the Parker bound [1]. A renewed interest in the field has been triggered by some models that would explain the anomalous flux of Ultra High Energy Cosmic Rays (UHECR) observed above the GZK cutoff as due to magnetic monopoles. There are essentially two classes of models. In the first scenario UHECR would have been produced in the annihilation of monopole-antimonopole pairs. The binding mechanism results however to be very inefficient, unless poles are connected by strings, and in this case they would not be detectable with standard techniques since they would not show a magnetic charge [6]. In the second case, light ultrarelativistic monopoles would produce showers in crossing the atmosphere thus simulating a UHECR event. A monopole flux at the level of the Parker bound would be sufficient to explain the observed rates [7]. If this is the case important progress might be done in the next few years by underwater/ice experiments, due to their large acceptances and sensitivities in the relativistic region.

Acknowledgments
The author gratefully acknowledges the MACRO Collaboration, in particular the members of the *rare particle working group*.

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